FINAL REPORT

"GaN Based Structures for NEA by MBE and Investigation of Nitrogen Species and Precursors for Optimum Layer Properties"

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Progress Made:

During the life of this grant, we have made substantial progress in the production, and processing of GaN based structures and in UV detectors and MODFETS based on GaN heterostructures. Below we give a succinct description of the progress made and list the publications that resulted from the support by ONR.

We have obtained:

ohmic contacts with resistivities below 10^{-7} Ohmcm^2 to n type GaN which are stable at 500°C,

Pt Schottky barriers with nearly a unity ideality factor which appear stable at operation temperatures of about 500 °C,

AlGaN/GaN MODFETs on sapphire substrates with 1.5 micron gate length exhibiting extrinsic transconductances of about 220 mS/mm, drain currents of about 600 mA/mm and breakdown voltages of over 100 V for a 1 μm gate-drain separation,

Inverted MODFETs on sapphire with extrinsic transconductances of about 80 ms/mm with lesser output negative conductance due to carrier confinement reducing the current path in the buffer layer,

AlGaN/GaN MODFETs on SiC with 1.5 micron gate length exhibiting extrinsic transconductances of about 180 mS/mm, drain currents of about 325 mA/mm with the negative output conductance prevalent on sapphire being absent,

GaN layers on (0001) ZnO have been grown which are smooth away from the interface, with optical properties of films comparable to the best on sapphire and better than the best on SiC and the c axis aligned with that of the substrate as determined by X ray and polarized reflectance.

We have fabricated GaN based Pin like detectors, with no anti-reflection coating, exhibiting responsivities of about 0.12 A/W corresponding to an internal quantum efficiency of about 60%, and near zero bias speed of response of about 9 ns. Though additional investigations are warranted, the speed appears to be limited by the RC time constant. At wavelengths >390 nm the responsivity drops by more than three orders of magnitude. Noise equivalent power at zero bias is limited by the instrumental noise level at 4 pW. Preliminary results with improved measurement set-up indicate the NEP to be in the tens of femtowatt.

The UV detectors are imperative in military systems because of the continuing proliferation and increasing lethality of anti-aircraft missiles pose a grave threat to military

aircraft. At altitudes below ~30,000 ft, the ultraviolet (UV) spectral region from 260-290 nm is nearly ideal for detecting missile plumes against a dark background.

The current UV missile warning sensors uses photomultiplier-based sensor arrays which are bulky, have limited sensitivity due to extensive optical filtering and photon-to-electron conversions and suffer from increased background noise due to detection of long wavelengths outside the solar-blind region. By comparison, solid state photodetectors offer the advantages of being compact, rugged, and potentially cheap. In addition, solid state detectors have near-unity quantum efficiency and offer superior rejection of long wavelength background light. This important application underscores the impact of our accomplishments in the UV detector area.

Most Recent Accomplishments in GaN on ZnO Substrates:

- Hamdani, A. Botchkarev, W. Kim, A. Salvador, Ö. Aktas, H. Morkoç, M. Yeadon, J. M. Gibson, S.-C. Y. Tsen, D. J. Smith, D. C. Reynolds, D. C. Look, K. Evans, C. W Litton, W. C. Mitchel, and P. Hemenger, "Optical properties of GaN grown on ZnO by Reactive MBE" Appl. Phys. Letts. Vol. 70, No. 4, pp. 467-469, (1997).

High quality wurtzite GaN epilayers have been grown on ZnO(0001) substrates by reactive molecular beam epitaxy. Photoluminescence and reflectivity measurements point to high quality presumably due to the near match of both the crystal lattice parameter and the stacking order between GaN and ZnO. In addition, the good films lack the characteristic yellow photoluminescence band. Any misorientation of the GaN epilayer planes with respect to the ZnO substrate is not detectable with polarized reflectivity. The x-ray double crystal diffraction measurements indicate this misorientation is much smaller than those for GaN epilayers on SiC and Al_2O_3.

- Hamdani , M. Yeadon, David. J. Smith, H. Tang, W. Kim, A. Salvador, A. E. Botchkarev, J. M. Gibson and H. Morkoç, " Microstructure and optical properties of epitaxial GaN on ZnO(0001) grown by reactive molecular beam epitaxy", J. Appl. Phys. in press.

High quality GaN epilayers has been grown on O and Zn surfaces of ZnO(0001) substrates by reactive molecular beam epitaxy. We present an investigation of the effect of the intermediate buffer layer on the structural and optical properties of the GaN films. The optical and structural characterization of both GaN epilayers and ZnO substrate have been performed using photoluminescence, reflectivity, x-ray double diffraction, atomic force microscopy and transmission electron microscopy. The optical results indicate that GaN is grown with compressive strain due to the difference in thermal expansion coefficient between GaN and ZnO. The surface roughness has been reduced by using an intermediate low temperature buffer layer of GaN. The photoluminescence spectra at low temperature of GaN/ZnO epilayers do not reveal any appearance of the well known midgap yellow signal. Linear polarized reflectivity and photoluminescence results indicate that GaN epilayers planes are not misoriented with respect to the ZnO substrate planes, this fact is confirmed by x-ray double diffraction measurements.

Hamdani, A. Botchkarev, H. Tang, W. Kim, and H. Morkoç "Effect of Substrate Surface Polarity and Buffer Layer on the Growth of GaN on ZnO by Molecular Beam Epitaxy" Appl. Phys. Lett., in press.

The effect of substrate surface polarity, O and Zn faces, on the quality of GaN epitaxial layers grown on ZnO(0001) substrates by reactive ammonia molecular beam epitaxy has been investigated. The possible effects dealing with the disparity in surface preparation of the two faces have been eliminated. Photoluminescence and reflectivity measurements demonstrate that the oxygen-face leads to higher quality GaN on ZnO compared to the zinc-face. We also present optical data obtained by using low temperature AlN, GaN and $In_xGa_{1-x}N$ buffer layers. The best result has been obtained with nearly lattice matched $In_{0.20}Ga_{0.80}N$ buffer layer.

Carrier dynamics in GaN/AlGaN quantum wells are pivotal in electronic and optoelectronic devices in this important material systems. While short carrier lifetimes in absence of non-radiative recombination lead to efficient light emission, in general it is sign of non-radiative recombination and extreme localization. By producing micro-disks, we were able to extend

the excitonic lifetimes in GaN/AlGaN quantum wells as outline below.

- A. Mair, K. C. Zeng, J. Y. Lin, H. Jiang, B. Zhang, L. Dai, H. Tang, A. Botchkarev, W. Kim, and H. Morkoç, "Optical Properties of GaN/AlGaN Multiple Quantum Well Microdisks" Appl. Phys. Lett., in press.

An array of micro-disks with diameter of about 9 μm and spacing of 50 μm has been fabricated by dry etching from a 50 _/50 _ GaN/$Al_xGa_{1-x}N$ (x_0.07) multiple quantum well (MQW) structure grown by reactive molecular beam epitaxy. Optical properties of these micro-disks have been studied by picosecond time-resolved photoluminescence (PL) spectroscopy. PL emission spectra and decay dynamics were measured at various temperatures and pump intensities. With respect to the original MQWs, we observe strong enhancement of the transition intensity and lifetime for both the intrinsic and barrier transitions. The intrinsic transition is excitonic at low temperatures and exhibits an approximate 10 fold increase in both lifetime and PL intensity upon formation of the micro-disks. This implies a significant enhancement of quantum efficiency in micro-disks and a bright future for III-Nitride micro-cavity lasers.

- ZnO epitaxial layers have been grown by MBE. These preliminary and successful attempts utilized sapphire substrate for cost reasons. Even then, films showed strong interference fringed below the gap at room temperature. Both water vapor and reactive oxygen supplied by an electron cyclotron resonance(ECR) source have been utilized for the group VI element. A substrate temperature range of 500 to 700 °C has been explored with higher substrate temperatures resulting in lower background carrier concentrations and stronger interference fringes. Plans are under way to repeat these experiments on ZnO substrates and explore even higher growth temperatures. Nominally, a growth rate of about 0.5 μm/hour has been employed. The films show sharp and strong bandedge absorption and excitonic emission. Mg has also been incorporated with resultant increase in the bandgap.

Publications resulting under this program:

"Wide Bandgap Nitrides and Devices", by H. Morkoç, Springer, Submitted.

S. N. Mohammad, and H. Morkoç, "Light Emitting Diodes" in Wiley Encyclopedia of Electrical Engineering and Electronics Engineering, Ed. J. Webster, John Wiley and Sons, Inc. Publishers, in press.

" Beyond SiC! III-V Nitride Based Heterostructures and Devices" by Hadis Morkoç, in SiC Materials and Devices, Ed. Y. S. Park, Academic Press, Willardson and Beer Series.

"Electronic and Optical Properties of III-V Nitride-based Quantum Wells and superlattices" by Hadis Morkoç, F. Hamdani, and Arnel Salvador, in Gallium Nitride, Eds. J. Pankove and T. Moustakas, in the Semiconductors and Semimetals Series Vol. 50, pp. 193-254, (1997). Eds. R. K. Willardsion and E. R. Weber, Academic Press

" Emerging GaN Based Devices" by S. N. Mohammad, A. Salvador, and H. Morkoç, Proc. IEEE, Vol. 83, pp. 1306-1355, October 1995.

" Progress and Prospects of Group III-V Nitride Semiconductors", by S. N. Mohammad and H. Morkoç, Progress in Quantum Electronics, PQE Vol. 20, Numbers 5 and 6, pp. 361-525, (1996), a monogram.

" High Luminosity Gallium Nitride Blue and Blue-Green Light Emitting Diodes", H. Morkoç and S. N. Mohammad, Science Magazine, Vol. 267, pp. 51-55, Jan. 6, 1995.

"III-V Nitrides and Silicon Carbide for Photonic Materials and Devices," H. Morkoç, in M.S. Gupta, ed., *CRC Handbook of Photonics*, pp. 49-84, , Boca Rotan, NY, 1997.

"GaN Based III-V Nitrides by Molecular Beam Epitaxy " H. Morkoç, A. Botchkarev, A. Salvador, and B. Sverdlov, Proceedings of the 8th International Conference on Molecular Beam Epitaxy, August 29-September 2, 1994, Osaka, Japan. J. of Crystal Growth, Vol. 150, pp. 887-891, (1995).

"Advances in GaN Based III-V Nitrides and Devices" H. Morkoç, Proceedings of the 8th Conference on Semi-Insulating Materials, June 6-10, 1994. Warsaw, Poland. in Proceedings of the Semi-Insulating III-V Materials, ed. M. Godlewski, pp. 53-59, 1994. World Scientific.

"Properties of GaN Films Grown Under Ga and N Rich Conditions with Plasma Enhanced MBE", by A. Botchkarev, A. Salvador, B. Sverdlov, J. Myoung, and H. Morkoç, J. Appl. Phys. Vol. 77. No. 9, pp. 4455-4458, (1995)

"Valence Band Discontinuity Between GaN and AlN Measured by X-Ray Photemission Spectroscopy" by G. A. Martin, S. T. Strite, A. Botchkarev, A. Agarwal, A. Rockett, W. R. L. Lambrecht, B. Segall, and H. Morkoç, Journal of Electronic Materials, APR, Vol. 24, N4, pp. 225-227.1995,

" Second Order Raman Spectroscopy of the Wurtzite Form of GaN" by S. Murugkar, R. Merlin, A. Botchkarev, A. Salvador, and H. Morkoç, J. Appl. Phys. Vol. 77. No.11, pp. 6042-6043, June 1, 1995.

" Dynamics of the Band-to-Impurity Transition in GaN Grown by Molecular Beam Epitaxy", by M. Smith, G. D. Chen, J. Y. Lin, H. Jiang, A. Salvador, B. N. Sverdlov, A. Botchkarev, and H. Morkoç, , Appl. Phys. Lett. Vol. 66 (No 25), pp. 3474-3476, (1995).

" TEM Charaterization of Structural Defects in Wurtzite GaN Grown on 6H SiC Using Plasma-Enhanced Molecular Beam Epitaxy",David J. Smith, D. Chandrasekhar, B. N. Sverdlov, A. Botchkarev, A. Salvador, and H. Morkoç, Appl. Phys. Lett. Vol. 67, No.13, pp. 1830-1832,(1995).

" Base Transit Time in GaN/InGaN Heterojunction Bipolar Transistors" S. N. Mohammad and H. Morkoç, J. of Appl. Phys. Vol. 78, pp. 4200-4205, (1995).

"Formation of Threading Defects in GaN and related Wurtzite films grown on non-isomorhic substrates", B. Sverdlov, G. A. Martin, and H. Morkoç, Appl. Phys. Lett. Vol.67, N. 14, pp. 2063-2065, (1995)..

" Electron-phonon Interaction in the wide bandgap semiconductor GaN" by S. J. Sheih, K. T. Tsen, D. K. Ferry, A.E.Botchkarev, B. N. Sverdlov, , A. Salvador, and H. Morkoç, Appl. Phys. Lett. Vol. 67, No. 12, pp. 1757-1759. (1995).

"High Transconductance-Normally-Off GaN MODFETs", by Özgür Aktas, W. Kim, Z. Fan. S.N. Mohammad, A. Botchkarev, A. Salvador, B. Sverdlov, and H. Morkoç, Electron. Letts. Vol. 31, No. 16, pp. 1389-1390, (1995).

" Ground and Excited State Exciton Spectra from GaN Grown by Molecular Beam Epitaxy", by D. C. Reynolds, D. C. Look, W. Kim, Ö. Aktas, A. Botchkarev, A. Salvador, H. Morkoç, and D. N. Talwar, J. of Appl. Phys. Vol. 80. No. 1, pp. 594-596, July 1, (1996).

"Very low Resistance Multi-layer Ohmic Contact to n-GaN" by Zhifang Fan, S. Noor Mohammad, Wook Kim, Özgür Aktas, Andrei E. Botchkarev, and Hadis Morkoç, Appl. Phys. Letts. Vol. 68, pp. 1672- 1674, (1996).

" Photoluminescence Studies of Band Edge Transitions in GaN Epitaxial Layers Grown by Molecular Beam Epitaxy" by G. D. Chen, M. Smith, J. Y. Lin, H. Jiang, A. Salvador, B. N. Sverdlov, A. Botchkarev, and H. Morkoç, J. of Appl. Phys., Vol 79, pp. 2675- 2683, (1996)

"Properties of a Si Doped GaN/AlGaN Single Quantum Well" by A. Salvador, G. Liu, W. Kim, Ö. Aktas, A. Botchkarev, and H. Morkoç,Appl. Phys. Lett. Appl. Phys. Lett. Vol. 67 (22) pp.3322-3324 (1995),

"Electrical Conduction in Platinum-Gallium Nitride Schottky Diodes" by K. Suzue, S. N. Mohamad, Z. F. Fan, W.Kim, Ö. Aktas, A. E. Botchkarev, and H. Morkoç, J. of Appl. Phys. Vol. 80, No. 6, pp. 4467-4478, October 15, 1996,

"Structural Properties of GaN Films Grown on Sapphire by Molecular Beam Epitaxy", by Q. Zhu, A. Botchkarev, W. Kim, Ö. Aktas, A. Salvador, B. Sverdlov, H. Morkoç, J. Tsen and D. J. Smith, Appl. Phys. Lett. Vol. 68, No. 8, pp. 1141-1143.(1996).

"Reactive Molecular Beam Epitaxy of Wurtzite GaN Grown with Ammonia: Material Characteristics and Growth Kinetics", by Wook Kim, Özgür Aktas, Andrei Botchkarev, and Hadis Morkoç, J. Appl. Phys. Vol. 79, No. 10, pp. 7657-7666, (1996) .

"Excitonic Recombination in GaN Grown By Molecular Beam Epitaxy", by M. Smith, G. D. Chen, I. Z. Li, I. Y. Lin, H. X. Jiang, A. Salvador, W. K. Kim, Ö. Aktas, A. Botchkarev, and H. Morkoç, Appl. Phys. Lett. Dec. 4, Vol. 67, N. 23, pp.3387-3389,(1995).

"Room-Temperature Stimulated Emission in GaN/AlGaN Separate Confinement Heterostructures Grown by Molecular Beam Epitaxy", by T. J. Schmidt, X. H. Yang, W. Shan, J. J. Song, A. Salvador, W. Kim, Ö. Aktas, A. Botchkarev, and H. Morkoç, Appl. Phys. Letts. Vol. 68, pp. 1820-18222, (1996),

"Theoretical Characteristics of AlGaN/GaN MODFETs" , by F. Stengel, S. N. Mohammad and H. Morkoç, J. Appl. Phys. Vol. 80 No. 5, pp 3031-3042, 1 September (1996).

" Near Ideal Platinum-GaN Schottky Diodes ", by S. N. Mohammad, Zhifang Fan, A. E. Botchkarev, W. Kim, Ö. Aktas, A. Salvador, and H. Morkoç, Electronics Letters, Vol. 32, pp. 598 (1996),

"On the incorporation of Mg and the role of oxygen, silicon and hydrogen in GaN prepared by Reactive Molecular Beam Epitaxy" by Wook Kim, A. E. Botchkarev, A. Salvador, G. Popovici, H. Tang, and H. Morkoç, J. Appl. Phys. Vol. 82(1), 1 July, pp. 219-226, 1997.

"Deep Center Hopping Conduction in GaN", by D. C. Look, D. C. Reynolds, W. Kim, Ö. Aktas, A. Botchkarev, A. Salvador, and H. Morkoç, Vol. 80, No. 5, pp. 2960-2962, (1996) ,

" Structural Defects due to Interface Steps and Polytypism in III-V Semiconducting Materials, A case study: HREM of the 2H AlN/6H SiC Interface", P. Vermaut, P. Ruterana, G. Nouet, and H. Morkoç, Philosophical Magazine, Vol. 75, No. 1, pp. 239-259

"Thermally Stimulated Current Trap in GaN" , by D. C. Look, Z-Q. Fang, W. Kim, Ö. Aktas, A. Botchkarev, A. Salvador, and H. Morkoç, Appl. Phys. Letts., Vol. 68, No. 26, pp. 3775-3777, June 24, (1996).

"Microstructure of Ti/Al and Ti/Al/Ni/Au ohmic contacts for n-GaN" , by Sergei Ruvimov, Zuzanna Liliental-Weber, Jack Washburn, K.J. Duxstad and E.E. Haller, S.N. Mohammad, Z. Fan, and H. Morkoç,Appl. Phys. Letts. Vol. 69, No. 11, pp. 1556-1558. September 9, (1996).

"Nonequilibrium Electron Distributions and Phonons in Wurtzite GaN" by K. T. Tsen, R. P. Joshi, D. K. Ferry, A. Botchkarev, B. Sverdlov, A. Salvador, and H. Morkoç, Appl. Phys. Letts., Vol. 68, No.21,pp. 2990-2992, May 20, (1996).

"Near ultraviolet luminescence of Be doped GaN grown by reactive molecular beam epitaxy using ammonia", by A. Salvador , W. Kim, Ö. Aktas, A. Botchkarev, Z. Fan and H. Morkoç, Appl. Phys. Letts. Vol. 69, No. 18, pp. 2692-2694, October 28, (1996).

"Mg-Doped P-Type GaN Grown by Reactive Molecular Beam Epitaxy", by Wook Kim, A. Salvador, A. E. Botchkarev, O. Aktas, S.N. Mohammad, and H. Morkoç, Appl. Phys. Letts. Vol. 69(4), pp. 559-561, 22 July (1996).

"Nature of Mg impurities in GaN" by J. Z. Li, Y. Lin, H. X. Jiang, A. Salvador, A. Botchkarev, and H. Morkoç, Appl. Phys. Letts. Vol. 69, No. 10, pp. 1474-1476, September 2, (1996).

"Suppression of Leakage Currents and Their Effect on the Electrical Performance of AlGaN/GaN MODFETs", by Z. Fan, S. N. Mohammad, Ö. Aktas, A. Botchkarev, A. Salvador, and H. Morkoç, Appl. Phys. Letts. 69(9), pp. 1229-1231, 26 August (1996).

"Oscillator Strengths for Band to Band Optical Processes in GaN Epilayers", by B. Gil, F. Hamdani, and H. Morkoç, Ö. Aktas, Z. Fan, A. Botchkarev, , M. Roth, T. Jenkins, L. T. Kehias, and H. Morkoç, "Microwave Performance of AlGaN/GaN Inverted MODFETs", IEEE Elect. Dev. Letts. in press, AFOSR, ONR Park and Wood.

"Optical Transitions in GaN/AlxGa1-xN Multiple Quantum Wells Grown by Molecular Beam Epitaxy" by M. Smith, J. Y. Lin, and H. X. Jiang, A. Salvador, A. Botchkarev, and H. Morkoç, Appl. Phys. Letts., Vol. 69, No. 17, pp. 2453-2455, October 21, (1996).

"High Temperature Characteristics of AlGaN/GaN Modulation Doped Field-Effect Transistors" by Özgur Aktas, Z.-F. Fan, S.N. Mohammad, A.E. Botchkarev and H. Morkoç, Appl. Phys. Letts. Vol. 69, No. 25, pp. 3872-3874, December 16, (1996).

"Similarities in the Bandedge and Deep-Center Photoluminescence Mechanisms of ZnO and GaN" by D. C. Reynolds, D. C. Look, B. Jogai, and H. Morkoç, Solid State Communications, Vol. 101, No. 9, pp. 643-646, (1997).

"Defects in and Applications of III-V Nitrides and Related Semiconductors", by Hadis Morkoç, Proc. of the International Conference on Defects in Insulating Materials, Wake Forest University, July 15-19, 1996, in Materials Science Forum, Vols. 239-241, pp. 119-144, (1996).

"Surface roughness of nitrided (0001) Al_2O_3 and AlN epilayers grown on (0001) Al_2O_3 by reactive molecular beam epitaxy", by Wook Kim, M. Yeadon, A. E. Botchkarev, S. N. Mohammad, J. M. Gibson, and H. Morkoç, JVST B, 15(4), pp. 921-927, Jul/Aug (1997).

"Optical properties of GaN grown on ZnO by Reactive MBE" by F. Hamdani, A. Botchkarev, W. Kim, A. Salvador, Ö. Aktas, H. Morkoç, M. Yeadon, J.M. Gibson, S.-C. Y. Tsen, D. J. Smith, D. C. Reynolds, D. C. Look, K. Evans, C. W Litton, W. C. Mitchel, and P. Hemenger, Appl. Phys. Letts. Vol. 70, No. 4, pp. 467-469, (1997).

"Dopant incorporation and Defects in, and Applications of III-V Nitrides and Related Semiconductors" by Hadis Morkoç, Proc. of the 8th International Symposium on the Physics of Semiconductors and Applications, Oct. 21-22, 1996. Seoul Korea.

"Microwave Performance of AlGaN/GaN Inverted MODFETs", by Ö. Aktas, Z. Fan, A. Botchkarev, , M. Roth, T. Jenkins, L. T. Kehias, and H. Morkoç, IEEE Elect. Dev. Letts. in press,

"Optical Properties of GaN/AlGaN Quantum Wells", by Roberto Cingoleni, G. Coli, R. Rinaldi, L. Calcagnila, H. Tang, A. Botckareve, W. Kim, A. Salvador, and H. Morkoç, Phys. Rev. B. in press.

"AlGaN/GaN Double Heterostructure Channel Modulation Doped Field Effect Transistors (MODFETs)", by Zhifang Fan, Changzhi. Lu , A. Botchkarev, H. Tang, A. Salvador, Ö. Aktas, W. Kim and H. Morkoç, Wook Kim, A. E. Botchkarev, A. Salvador, G. Popovici, H. Tang, and H. Morkoç, "On the incorporation of Mg and the role of oxygen, silicon and hydrogen in GaN prepared by Reactive Molecular Beam Epitaxy" J. Appl. Phys. Vol. 82(1), 1 July, pp. 219-226, 1997.

G. Y. Xu, A. Salvador, W. Kim, Z. Fan, C. Lu, H. Tang, H. Morkoç, G. Smith and M. Estes, " Ultraviolet Photodetectors based on GaN p-i-n and AlGaN(p)-GaN(i)-GaN(n) Structures" Appl. Phys. Letts. Vol. 71, No. 15, pp. 2154-2156, (1997).

M. Yeadon, F. Hamdani, G. Y. Xu, A. Salvador, A.E. Botchkarev, J. M. Gibson, H. Morkoç, "Surface Morphology and Optical Characterization of GaN grown on (0001) by Radio Frequency Assisted Molecular Beam Epitaxy", Appl Phy Lett. in press.

S. Noor Mohammad, Andrei E. Botchkarev, Arnel Salvador, Wook Kim, Ozgur Aktas, and Hadis Morkoc, "Proposed explanation of the anomalous doping characteristics of III-V nitrides", Philosophical Magazine B, in press.

G. Popovici, G. Y. Xu, A. Botchkarev, W. Kim, H. Tang, A. Salvador, H. Morkoç, R. Strange and J. O. White, " Raman Scattering and Photoluminescence of Mg Doped GaN Films Grown by Molecular Beam Epitaxy" Appl. Phys. Letts. Pending. J Appl Phy, in press.

G. Popovici, G. Y. Xu, A. Botchkarev, W. Kim, H. Tang, A. Salvador, H. Morkoç, R. Strange and J. O. White, " Raman Scattering and Photoluminescence of Mg Doped GaN Films Grown by Molecular Beam Epitaxy" Materials Research Society Spring Meeting, April ..... (1997)

Galina Popovici , Wook Kim , Andrei Botchkarev , Haipeng Tang, James Solomon, and Hadis Morkoç, "Impurity Contamination of GaN Epitaxial Films From Sapphire, SiC, and ZnO Substrates". Appl. Phys. Lett. pending ..... (1997).

Salman Mitha, Robert Clark-Phelps, Jon W. Erickson, Y. Gao, Wook Kim, and Hadis Morkoç, "Characterization of the substrate/film interface in GaN films by image depth profiling secondary ion mass spectrometry(SIMS)". Materials Research Society Spring Meeting, April ..... (1997)

F. Hamdani, A. Botchkarev,H. Tang, W. Kim, and H. Morkoç "Effect of Substrate Surface Polarity and Buffer Layer on the Growth of GaN on ZnO by Molecular Beam Epitaxy" Appl. Phys. Lett., in press.

M. Smith , J. Y.Lin, H. X. Jiang, A. Khan, Q. Chen, A. Salvador, A. Botchkarev, and H. Morkoç, "Optical Transitions and Recombination lifetimes in GaN and InGaN Epilayers, and InGAN/GaN and GaN/AlGaN multiple Quantum Wells", Fall'96 meeting of the Materials Research Society, Dec. 1996. , Mat. Res. Soc. Symp. Proc. Vol. **449**, p. 829 (1997).

J. Z. Li, J. Y.Lin, H. X. Jiang, A. Khan, Q. Chen, A. Salvador, A. Botchkarev, and H. Morkoç, "Persisitent Photconductivity in p-type GaN epilayers and N type AlGaN / heterostructures", Fall'97 meeting of the Materials Research Society, Dec. 1996.

M. Smith , J. Y.Lin, H. X. Jiang, A. Khan, Q. Chen, A. Salvador, A. Botchkarev, and H. Morkoç, "Phonon-Exciton Interaction in InGaN/GaN and GaN/AlGaN multiple Quantum Wells", Appl. Phys. Lett. in press .

G. Y. Xu, A. Salvador, W. Kim, Z. Fan, C. Lu, H. Tang, H. Morkoç, G. Smith, M. Estes, B. Goldenberg, W. Yang, and S. Krishnankutty, "GaN and AlGaN(p)/GaN p-i-n Ultraviolet Photodectectors " Device Research Conference, Ft. Collins, CO, June 23,1997.

Ö. Aktas, Z. Fan, Changzhi. Lu, A. Botchkarev, H. Tang, S. N. Mohammad, M. Roth,and H. Morkoç, "High Current and Transconductance AlGaN/GaN MODFETs at Elevated Temperatures", Device Research Conference, Ft. Collins, CO, June 23, 1997.

K. C. Zeng , J. Y.Lin, H. X. Jiang, A. Salvador, G. Popovici, H. Tang, W. Kim, and H. Morkoç, "Effect of Well Thickness and Si-Doping on the Optical Emission Properties of GaN/AlGaN Multiple Quantum Wells", Appl. Phys. Lett. 71, 1368 (1997), (1997).

882. F. Hamdani , M. Yeadon, David. J. Smith, H. Tang, W. Kim, A. Salvador, A. E. Botchkarev, J. M. Gibson, A. Y. Polyakov, M. Skowronski, and H. Morkoç, " Microstructure and optical properties of epitaxial GaN on ZnO(0001) grown by reactive molecular beam epitaxy", J. Appl. Phys. Vol. 83, 15 January (1998).

F. Hamdani, A. Botchkarev, W. Kim, A. Salvador, Ö. Aktas, H. Morkoç, M. Yeadon, J.M. Gibson, S.-C. Y. Tsen, D. J. Smith, "Optical properties of GaN grown on ZnO by Reactive MBE" J. of Appl. Phys. 70(4), 27 January 1997.

883. Zhonghui Wang, Deda M. Diatezua, Dae-Gyu Park, Z. Chen, Hadis Morkoç, and Angus Rockett, " Plasma Nitridation of a Thin Si Layer on GaAs: A Photoelectron Spectroscopy Study", J. Appl. Phys. pending. NSF, DOE. AFOSR.

S.-C. Y. Tsen and David. J. Smith, K. T. Tsen, W. Kim and H. Morkoç, "Microstructural Investigation of Mg-doped p-type GaN - Correlation between High-Resolution Electron Microscopy and Raman Spectroscopy" --- J. Appl.
Phys. pending,

P. Vermaut, P. Ruterana, G. Nouet, A. Salvador and H. Morkoç, " Polarity Study by CBED of GaN Films Grown on $(0001)_{Si}$ 6H-SiC", Proc. of the Xth Microspcopy of Semiconducting Meterials Conference, 1997 Oxford.

P. Vermaut, P. Ruterana, G. Nouet, A. Salvador and H. Morkoç, "HREM and CBED Studies of Polarity of Nitride Layers with Prosmatic Defects Grown Over SiC" Materials Research Sysmposium D, San Francisco, April, 1997.

P. Vermaut, P. Ruterana, G. Nouet, A. Salvador and H. Morkoç, " Geometrical Analysis of Steps at the 2H-AlN/6H SiC Interface" Interface Science and Materials Interconnection, Proc. of JIMIS-8, pp. 331-334, (1996)., The Japan Institute of Metals.

P. Vermaut, P. Ruterana, G. Nouet, A. Salvador and H. Morkoç," Polarity of Epilayers and (1bar21bar0) Prismatic Defects in GaN and AlN Grown on $(0001)_{Si}$ 6h-SiC", Accepted in Phil. Mag. 4/14/96.

G. Y. Xu, A. Salvador, A. Botchkarev, W. Kim, Z. Fan, C. Lu, H. Tang, H. Morkoç, G. Smith, and M. Estes, "High Speed, Low Noise Ultraviolet Photodetectors Based on GaN p-i-n and AlGaN(p)-GaN(i)-GaN(n) Structures", Proc. of ICSC III-N '97, Stockholm Sweden Aug. 1997.

F. Hamdani , M. Yeadon, David. J. Smith, H. Tang, W. Kim, A. Salvador, A. E. Botchkarev, J. M. Gibson, and H. Morkoç, " Growth and characterization of high quality

epitaxial GaN on ZnO(0001) by reactive molecular beam epitaxy" Proc. of ICSC III-N '97, Stockholm, Sweden, Aug. 31, 1997.

L Calcagnile, G Coli, R. Rinaldi, R. Cingolani, H. Tang, A. Botchkarev, W. Kim, A. Salvador, H. Morkoç, " Ultraviolet stimulated emission in GaN/AlGaN multiple quantum wells" Proc. of ICSC III-N '97, Stockholm, Sweden, Aug. 31, 1997.

G Colli, L. Calcagnile, R. Rinaldi, R. Cingolani, H. Tang, A. Botchkarev, W. Kim, A. Salvador, H. Morkoç, "One and Two-Photon Absorption Spectroscopy of GaN/AlGaN Quantum Wells" Proc. of ICSC III-N '97, Stockholm, Sweden, Aug. 31, 1997.

G. Nouet, P Vermaut, V Potin, P Ruterana, A Salvador, H Morkoç, "The Atomic Structure of Prismatic Planar Defects in GaN/AlN Grown Over Silicon Carbide and Sapphire Substrates" Proc. of ICSC III-N '97, Stockholm, Sweden, Aug. 31, 1997.

G. Colli, L. Calcagnile, R. Rinaldi, R. Cingolani, H. Tang, A. Botchkarev, W. Kim, A. Salvador, H. Morkoç, "One and Two-Photon Absorption Spectroscopy of GaN/AlGaN Quantum Wells" Phys. Rev. B Rapid Communication, pending.

M. Yeadon, M. T. Marshall, F. Hamdani, S. Pekin, H. Morkoç, and J. M. Gibson, " In-Situ TEM of AlN Growth by Nitridation of (0001) α-Al_2O_3", J. Appl. Phys. pending.

900. J. L. LoPresti, S. C. Webb, R. T. Williams, W. Kim, H, Morkoç, A. E. Wickenden and D. D. Koleske, " Study of GaN Films by Pulsed Laser Photoelectron Spectroscopy" Presented at the 9th International Conference on Radiation in Insulators , September 14-19,1997, Knoxville,

901. R. A. Mair, K. C. Zeng, J. Y. Lin, H. Jiang, B. Zhang, L. Dai, H. Tang, A. Botchkarev, W. Kim, and H. Morkoç, "Optical Properties of GaN/AlGaN Multiple Quantum Well Microdisks" Appl. Phys. Lett., in press.

902. W. Y. Ho, K. Y-Tong, Charles Surya, and Hadis Morkoç, " Characterization of Flicker Noise in GaN Based MODFETs at Low Drain Biases" IEEE Trasanctions on Electron Devices, pending.

903. H. Tang, W. Kim, A. Botchkarev, G. Popovici, F. Hamdani and H. Morkoç, "Analysis of Carrier Mobility and Concentration in Si-doped GaN Grown by Reactive Molecular Beam Epitaxy" Solid State Electronics, pending.

904.P. Lefebvre, J. Allègre, B. Gil, A. Kavokin[1] and H. Mathieu, W. Kim, A.Salvador, A. Botchkarev and Hadis Morkoç, "Recombination Dynamics of Free and Localized Excitons in GaN / $Ga_{0.93}Al_{0.07}N$ Quantum Wells" Phys, Rev. B pending.